DEM Integrity Monitor Experiment (DIME) Flight Test Results

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ABSTRACT

This paper discusses flight test results of a Digital Elevation Model (DEM) integrity monitor. The DEM Integrity Monitor Experiment (DIME) was part of the NASA Synthetic Vision System (SVS) flight trials at Eagle-Vail, Colorado (EGE) in August/September, 2001. SVS provides pilots with either a Heads-down Display (HDD) or a Heads-up Display (HUD) containing aircraft state, guidance and navigation information, and a virtual depiction of the terrain as viewed "from the cockpit". SVS has the potential to improve flight safety by increasing the situational awareness (SA) in low to near zero-visibility conditions to a level of awareness similar to daytime clear-weather flying. This SA improvement does not only enable low-visibility operations, but may also reduce the likelihood of Controlled Flight Into Terrain (CFIT). Because of the compelling nature of SVS displays high integrity requirements may be imposed on the various databases used to generate the imagery on the displays even when the target SVS application does not require an essential or flight-critical integrity level. DIME utilized external sensors (WAAS and radar altimeter) to independently generate a "synthesized" terrain profile. A statistical assessment of the consistency between the synthesized profile and the profile as stored in the DEM provided a fault-detection capability. The paper will discuss the basic DIME principles and will show the DIME performance for a variety of approaches to Runways 7 and 25 at EGE. The monitored DEMs are DTED Level 0, USGS with a 3-arcsec spatial resolution, and a DEM provided by NASA Langley. The test aircraft was a Boeing 757-200.

Keywords: synthetic vision systems, terrain database, digital elevation model, integrity, spatial resolution.

1. INTRODUCTION

Synthetic Vision Systems (SVS) provide pilots with a virtual visual depiction of the external environment. This depiction can be portrayed on any flight-qualified display media. Prototype implementations have used a Head-Down Display (HDD) and/or a Head-Up Display (HUD) to provide aircraft state (e.g. altitude, attitude, airspeed, etc.), guidance and navigation information, and a perspective depiction of the terrain as viewed "from the cockpit". Other types of information can also be presented such as obstacles, traffic, and weather. SVS has the potential to improve flight safety by increasing pilot situational awareness (SA) in low visibility conditions to a level of awareness similar to daytime clear-weather flying. NASA has been investigating SVS as a mitigation strategy for accident categories such as Controlled Flight Into Terrain (CFIT), runway incursions, low visibility and loss-of-control scenarios; along with the ability to fly advanced precision approach procedures [1]. In addition, the Federal Aviation Administration (FAA) has mandated Terrain Awareness and Warning Systems (TAWS) for nearly all aircraft [2] to increase pilot's SA with respect to terrain. The major difference between TAWS and SVS is that SVS is being designed for applications ranging from purely advisory systems to flight-critical systems, whereas TAWS is currently required only as an advisory system.

1.1 Integrity

The term integrity is used frequently in the aviation community as a quality metric. Unfortunately, several segments of the community interpret integrity differently, so it is important to clearly define the term integrity, as its definition is central to this paper's discussion. Specifically, there are three definitions of integrity that are relevant to this research. For the purposes of this paper, they will be described as system integrity, data integrity, and data processing integrity. System integrity refers to the ability of the system to provide timely warnings to users when the system should not be used for its intended function. The integrity of display systems like SVS is most often quantified using the metric Pr(HMI) - the probability of hazardously misleading information being provided to pilots.

With respect to SVS terrain databases, required data integrity will depend on (1) the intended use of the data by the pilot and (2) the architecture of the system in which the data resides. One approach to illustrate this concept is to consider multiple levels of data integrity that correspond to the application's criticality (or impact on safety). For example, ICAO and RTCA delineate five levels of loss of system integrity due to data errors that result in specified failure conditions. Specifically, [3] and [4] describe a loss of integrity as when data errors could cause or contribute to the failure of a system function resulting in a *catastrophic, severe-major/hazardous, major, minor, or no effect* failure condition. These five failure conditions correspond to a range of safety margins from loss of human life to no effect at all. The hazard level associated with particular data in a particular system is determined by a *Functional Hazard Analysis (FHA).* Terrain database integrity is related to system integrity in that system integrity can be compromised if terrain data errors exist in the database and lead to HMI that is not detected by the operational system.

To ensure that data is not corrupted during processing and/or distribution, ICAO has established guidelines for data processing integrity [5][6]. ICAO defines data processing integrity as the degree of assurance that aeronautical data and its value have not been altered since the data origination or an authorized amendment [5]. To provide guidance to data processors and/or distributors, RTCA has published guidelines for data processing procedures that are intended to help ensure that the resulting data is no worse than the source data [7]. It is important to note that it is expected that the majority of terrain data that is stored on aircraft as part of an SVS or TAWS will not have a stated integrity with respect to the source data itself. The integrity specified with these data will only refer to "data processing" integrity [8][9]. This is primarily due to the fact that the amount of validation required to establish an integrity value for such large data sets is viewed as cost prohibitive.

1.2 Digital elevation models

Geo-spatial terrain databases, that may be used to depict terrain information on SVS displays, are referred to as Digital Elevation Models (DEMs). A variety of sources from both the public and private sectors provide DEMs, and these DEMs are specified by a number of parameters. These parameters include the post-spacing or spatial resolution, the horizontal and vertical references or datums, and the circular and linear error probabilities. The circular error probability (CEP) is used for the horizontal accuracy specification of the post position, whereas the linear error probability (LEP) is used to specify the accuracy in the vertical direction (height). Assuming that the circular and linear errors are random and normally distributed with zero-mean, the standard deviations in the horizontal and vertical directions, can be derived by dividing the 90% CEP and 90% LEP by 1.645. The standard deviation in the horizontal direction refers to the standard deviation of the error radius from the true post location using a two-dimensional polar coordinate frame.

1.3 Integrity monitoring approach

When utilizing terrain elevation databases in flight-critical systems, it is imperative to avoid the display of hazardous misleading terrain information (HMTI). HMTI can be the result from insufficient DEM spatial resolution, inappropriate coloring/texturing, or excessive DEM errors. The severity of the hazard will depend on (1) the specific flight operation being conducted, and (2), how the terrain depiction is used by pilots during this operation. This paper describes operational testing of a real-time terrain database integrity monitor that can reduce the probability of an undetected database error being inadvertently presented to the pilot. The proposed integrity monitor concept has been previously described in [10][11][12]. For this specific architecture, sensor information from the Global Positioning System (GPS), three radar altimeters, and augmentation information received from the Wide-Area Augmentation System (WAAS) are used to generate a synthesized, or "sensed", elevation profile. This profile is compared to the terrain database elevation profile in the statistical manner described in [10], and if significant inconsistencies exist between the two terrain profiles, an integrity alarm is generated.

1.4 Flight test objectives

Although the DEM integrity monitor concept had been previously flown on other aircraft [11][12], the SVS testing at EGE provided a unique opportunity to further evaluate the operational readiness of the technology. Specifically, the objectives of the DIME flight-testing at EGE were three-fold: (1) characterize operational behavior of the system using the Commercial Off The Shelf (COTS) B-757 triple-redundant radar altimeter set; (2) assess the quality of multiple DEMs provided by multiple industry and government organizations; and (3) observe the performance of the monitor in a region characterized by severe terrain undulations. Results are presented relative to these three primary objectives.

2. FLIGHT TEST ENVIRONMENT

2.1 Test aircraft and SVS implementation

The Airborne Research Integrated Experiments System (ARIES) is a Boeing 757-200 owned and operated by NASA's Langley Research Center (Figure 1). As many as 12 test pallets/research workstations can be configured in the aft cabin while the forward flight deck can host an evaluation pilot in the left-seat, two safety pilots, and a research observer.

Workstations in the cabin provide basic flight-test capabilities (e.g. video/data recording, aircraft systems interfaces, and power), as well as platforms for prototype test equipment provided by researchers. During the testing at EGE, prototype SVS displays were provided to evaluation pilots from the airlines, the FAA, and Boeing (Figure 2). It is important to note that for this test, the integrity monitor functions were isolated from the SVS display concepts being presented to the test pilots. Subsequent work will define appropriate means of informing the pilot during flight of loss of terrain database integrity.

Figure 1. (a) B-757 ARIES test aircraft, (b) B-757 at EGE

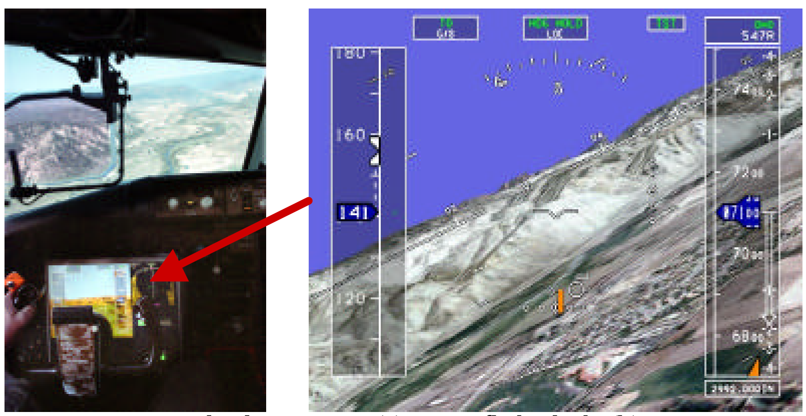


Figure 2. SVS display concept (a) B-757 flight deck, (b) SVS HDD

2.2 Operational environment

During the testing at EGE, the test aircraft flew primarily two distinct paths depending on the selected runway (7 or 25). Each path was broken into three segments: approach, runway fly-over, and departure. The approach to runway 25 was basically a straight-in ILS approach, while the approach to runway 7 required a circling maneuver at the EGE pattern altitude. The two departure procedures called for a minimum climb-out gradient emulating single-engine out operations. Runway fly-overs were at or above 50 feet (AGL). These flight paths are shown in Figure 3 superimposed on the terrain contours in the area. 118 of these operations were completed over a period of three weeks. The integrity monitor operated as long as terrain was within the range of the radar altimeters (<2500 feet AGL). This constituted about four minutes for an approach to runway 25, six minutes for an approach to runway 7, 3.5 minutes for a departure from runway 25, and 2.5 minutes for a departure from runway 7. The duration of the runway fly-over segments was about one minute.

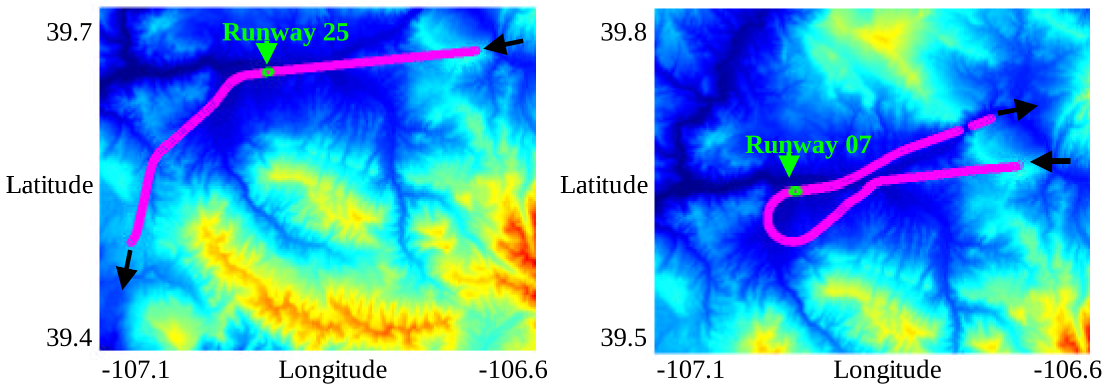


Figure 3. Flight profiles to (a) runway 25, (b) runway 07.

3. DIME EQUIPMENT

The DIME equipment consisted of a Fieldworks ruggedized computer functioning as a terrain database server with real-time integrity monitor capability. To obtain external sensor information for the purpose of consistency checking, the computer was interfaced via ARINC busses (A429) to three ARINC 707 Radar Altimeters, RAs, (left, center, and right), three ARINC 704 Inertial Reference Units, IRUs, (left, center, right), and an ARINC 743 Rockwell-Collins prototype WAAS receiver. A block diagram of the DIME equipment installation in the ARIES B-757 is shown in Figure 4. Note that Pallet (workstation) 2 housed the WAAS equipment. Pallet 7A (Wire Interface Unit) provides data from the standard B-757 equipment such as the IRUs. Pallet 16 housed the DIME Fieldworks computer.

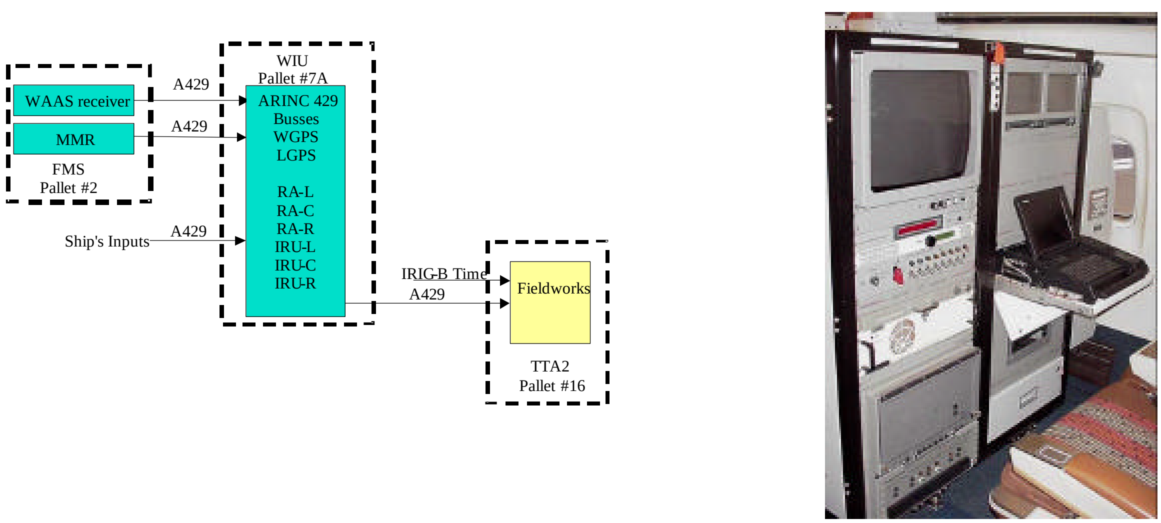


Figure 4. DIME – (a) equipment installation on B-757 ARIES, (b) Pallet

In addition, the ARIES B-757 carried two Ashtech Z-12 Kinematic GPS (KGPS) receivers onboard to establish a truth reference. Figure 5 shows the subcomponents of the Fieldworks ruggedized computer: a Condor Engineering ARINC interface card that supported reception of 8 ARINC 429 channels, and a Datum Inc. timing card that is interfaced to the ship's GPS-based timing reference. During the EGE flight trials, the timing interface card was not used, instead, the data time tags were established by the GPS UTC time and ARINC Interface card local clock. Note that for this test, DIME had no visual or aural components that were presented to the pilots.

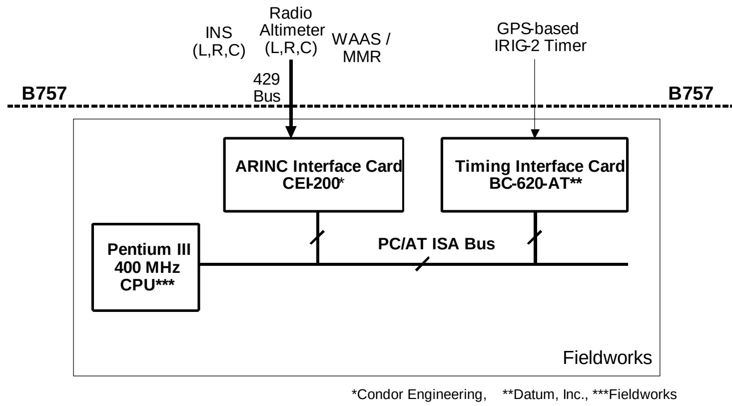


Figure 5. Fieldworks platform for DIME.

Three terrain databases were installed on the Fieldworks database server and monitored in real-time: DTED level 0 terrain data, a USGS 1-degree product, and a USGS 7.5-minute product processed and delivered by Jeppesen. DTED level 0 is characterized by a latitude and longitude post-spacing (or resolution) equal to 30 arc-seconds (~900m). The vertical datum for DTED level 0 is mean seal level (MSL) as defined by EGM 96 [13]. The USGS 1-degree product can be downloaded from USGS' website and has a spatial resolution of 3 arc-seconds (~90 m). Its vertical datum in the continental United States (CONUS) is the NGVD 29. The last terrain database is derived from the USGS 7.5-minute product and is characterized by a post-spacing of 1 arc-second (~30m). For DIME this database was down-sampled to a spatial resolution of 3 arc-second for a direct comparison with the USGS 1-degree data. In the remainder of this paper, the USGS 1-degree product will be referred to as USGS, whereas the USGS 7.5-minute product will be referred to as JEPP. The horizontal datum for all three products was WGS '84.

The nominal vertical error performance of the three radar altimeters onboard the ARIES B-757 is specified as follows:

$$\text{1.0 ft or 2\% of range, whichever is greater} \tag{1}$$

In general the vertical accuracy of WAAS, a form of Differential GPS (DGPS), is on the order of $?_V$ = ~2.5m, whereas the KGPS truth reference has a vertical accuracy of about $?_V$ = ~0.2m. The IRU data is being collected to investigate correlations between attitude and radar altimeter sensor behavior.

4. DIME PROCESSING

A block diagram of the DIME processes is shown in Figure 6. The incoming ARINC data is decoded and time-tagged: a DGPS (WAAS) position (latitude, longitude) and height MSL, h_{DGPS}; a radar altimeter height above ground level (AGL), h_{RA}; and roll pitch and heading from the IRUs. Based on the received DGPS position, the height of the terrain is retrieved from the terrain database, h_{DEM}. Because h_{DEM} corresponds to the height of the terrain directly below the aircraft, this height is referred to as the "plumb-bob height".

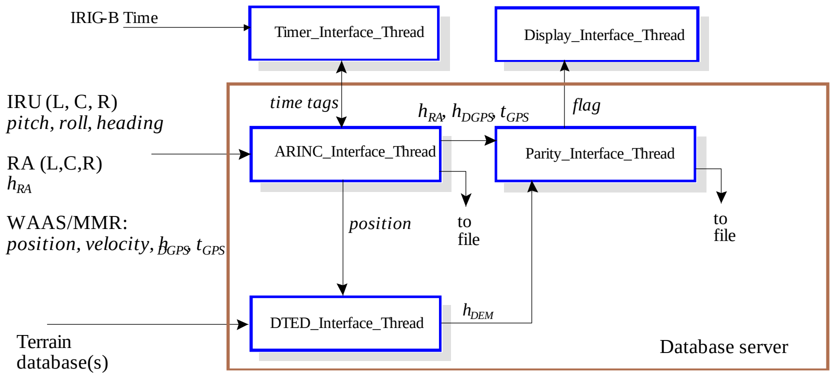


Figure 6. DIME processing block diagram.

[10] describes in detail how h_{DEM} , h_{DGPS}, and h_{RA} are used to generate a test-statistic that can be used to measure the consistency between the synthesized height (the height derived from h_{RA} and h_{DGPS}) and the terrain database height (h_{DEM}). The test statistic is given by the mean square difference of the synthesized and terrain database elevations:

$$T = \frac{1}{\sigma_P^2} \sum_{i=0}^{N-1} \left(h_{DGPS}(t_i) - h_{RA}(t_i) - l_{arm} - h_{DEM} \right)^2 \qquad (2)$$

where l_{arm} is the lever arm, correction between the radar altimeter antenna and the DGPS (or WAAS) antenna, and σ_P is the standard deviation of the nominal error performance of the disparity metric: h_{DGPS} - h_{RA} - h_{DEM}. [10]. N is referred to as the integration time and is directly related to the time -to-alert. During the flight tests, N was set to 50, whereas σ_P was set to 18.9m. Assuming an a priori terrain database failure rate of 10^{-2}, a probability of fault-free detection (or false alarm) of 0.99? 10^{-4} and a probability of missed detection of 10^{-9}, yields a test statistic threshold equal to T_D = 96. An alert will be generated in some fashion if the T-value of equation 2 exceeds T_D.

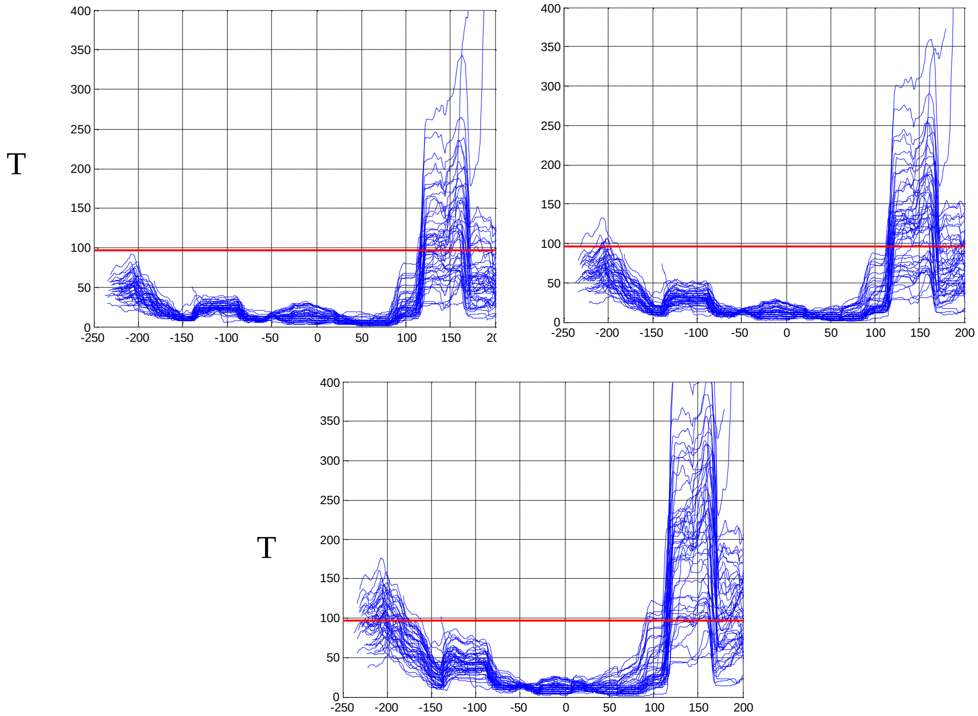
T-values can be generated based on each of the individual radar altimeter measurements, h_{RA1}, h_{RA2}, and h_{RA3}. During the flight-tests the T-values for each of the radar altimeters were displayed simultaneously. In an operational environment a voting scheme, such as mid-value select, must be applied to decide if an alert must be generated.

5. RESULTS

Of the 118 flight operations described in Section 2, 100 complete datasets were derived; 48 to runway 25, and 52 to runway 07. Note that not all flights (approaches/departures) to each of the runways followed the same procedure as described in Section 2. Further, turbulent weather conditions were encountered on some of the flights.

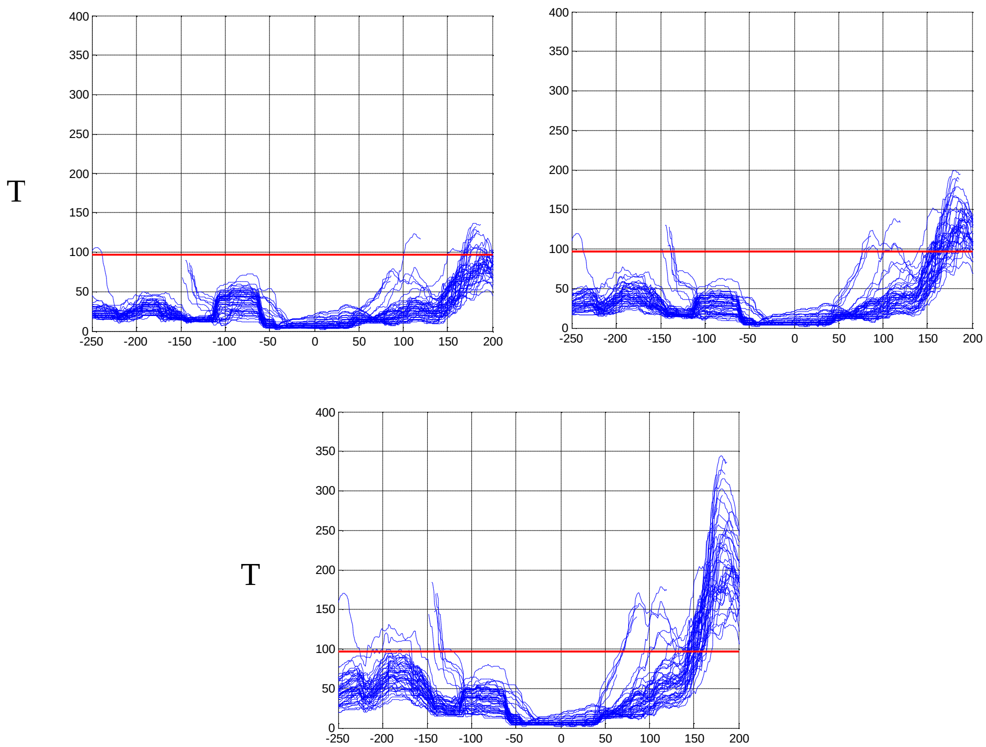
5.1 T-value results for WAAS/JEPP

Figures 7a, 7b, and 7c show the T-values for all approaches to runway 25 for radar altimeters 1 (left), 2 (center), and 3 (right), respectively. The thick horizontal line indicates the test statistic threshold T_D. Figures 8a, 8b, and 8c show the T-values for all approaches to runway 07 for radar altimeters 1 (left), 2 (center), and 3 (right), respectively.



(Time) m inus (Threshold crossing time) [sec]

Figure 7. Approach to runway 25 - (a) top-left: radar altimeter 1, (b) top -right: radar altimeter 2, (c) bottom: radar altimeter 3.



(Time) minus (Threshold crossing time) [sec]

Figure 8. Approach to runway 07 - (a) top-left: radar altimeter 1, (b) top -right: radar altimeter 2, (c) bottom: radar altimeter 3.

Figures 7 and 8 show a large number of T-values that exceed the threshold T_D. To analyze these apparent integrity violations tables 1 and 2 show the percentage of points (time-units) at which the T-value exceeds the threshold of 96 for runways 25 and 07, respectively. The total time-axis is divided into three intervals: time-to-runway-threshold > 2 minutes, time-after-runway-threshold > 1 minute, and the time interval directly around the runway threshold crossing. The results are shown for all three radar altimeters.

Table 1. Threshold violations (on a point basis) per radar altimeter per time interval for approach to runway 25.

Time interval	**Radar altimeter 1 (left)**	**Radar altimeter 2 (center)**	**Radar altimeter 3 (right)**
Before –120	0%	0.41%	4.44%
-120 - +60	0%	0 %	0%
After +60	11.08%	13.21%	19.19%

Table 2. Threshold violations (on a point basis) per radar altimeter per time interval for approach to runway 07.

Time interval	**Radar altimeter 1 (left)**	**Radar altimeter 2 (center)**	**Radar altimeter 3 (right)**
Before –120	0.19%	0.58%	5.13%
-120 - +60	0%	0 %	0.00%
After +60	1.56%	7.68%	13.13%

In the interval –120 to +60 no integrity alerts are observed. However for the other two time-intervals a relative high percentage of threshold violations occur. Are these violations false alerts or true detections? One effect can be identified as the main cause of the high T-values during these time intervals: the off-nominal behavior of the radar altimeter. The integrity threshold calculation is based on the radar altimeter error specified at lower altitudes. However, the radar altimeter error is a function of altitude as can be seen from Equation 1. Hence, at higher altitudes the error contribution of the radar altimeter is large compared to the other error contributors: DGPS, vegetation, and the terrain database. This effect cannot be classified as off-nominal, but is unaccounted for in the computation of ? $_P$. Defining ? $_P$ as a function of the altitude AGL would be a more realistic model, but is more complicated to implement and introduces a problem with respect to independence: what sensor can be used to determine the height AGL? Figure 9 shows the altitude AGL as measured by radar altimeter 1 for the approaches to runway 25 and 07.

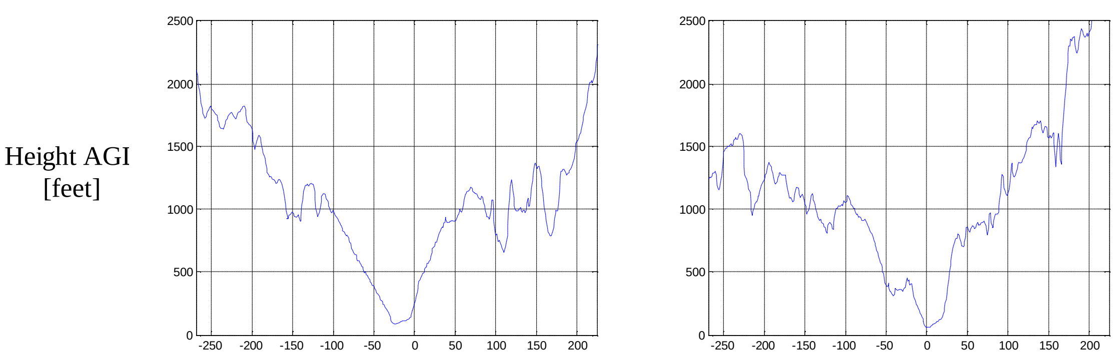


Figure 9. Altitude AGL for (a) approach to runway 25, (b) approach to runway 07.

According to the radar altimeter specification the error introduced by the sensor is about 2% of the altitude at higher altitudes. Therefore at higher altitudes the error can have a magnitude as large as 15m. This is a significant error compared to the ? = 18.2m nominal error of the terrain database. The frequency and temporal character of the radar altimeter is furthermore unspecified in the radar altimeter specification; a low-frequency error is more likely to cause increasing T-values.

Figures 7a through 7c and 8a through 8c show a strong inconsistency of the T-values among the left, center, and right radar altimeter. Apart from calibration differences between the physical units, two effects may cause the three radar altimeters to yield different but increasing T-value trends: (1) errors introduced due to banking at higher altitudes above terrain with significant undulations, and (2) illumination of a larger area by the RA main beam. Figure 10 shows an illustration of the latter effect. At higher altitudes a larger terrain surface area is illuminated. For pulsed radar altimeters, this may cause the RA to measure the closest point or strongest reflection within the illuminated area. For Frequency Modulated Continuous Wave (FM-CW) radar altimeters, such as the units used by the ARIES B-757, the strongest specular reflection will be tracked. One method to compensate for this effect in pulsed radar altimeters is the so-called "spot" algorithm [14]. The "spot" algorithm considers all points illuminated by the radar altimeter (the so-called spot) in the calculation of the measured radar altimeter height. Note from Figure 11 that at higher altitudes the error introduced by this effect becomes more pronounced in areas with large undulation such as EGE and surrounding areas.

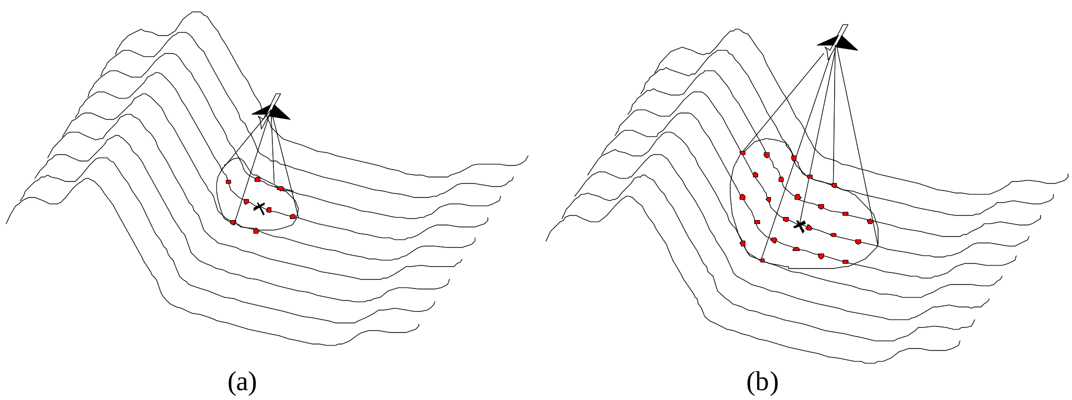


Figure 10. Roll-effect illustrated at lower (a) and higher (b) altitudes.

Bank maneuvers cause the radar altimeter to point off to the side instead of vertical along a virtual plum bob. This pointing error causes the radar altimeter to measure a distance other than the plumb bob height. This effect could be accounted for but requires the use of attitude information from the ship's IRUs. Figure 11 shows a strong correlation between the bank maneuver and a significant increase of the *T*-values around t= 140s. Note that due to the integration time of N = 50 seconds, the *T*-value curve does not get to its maximum until t = 180s.

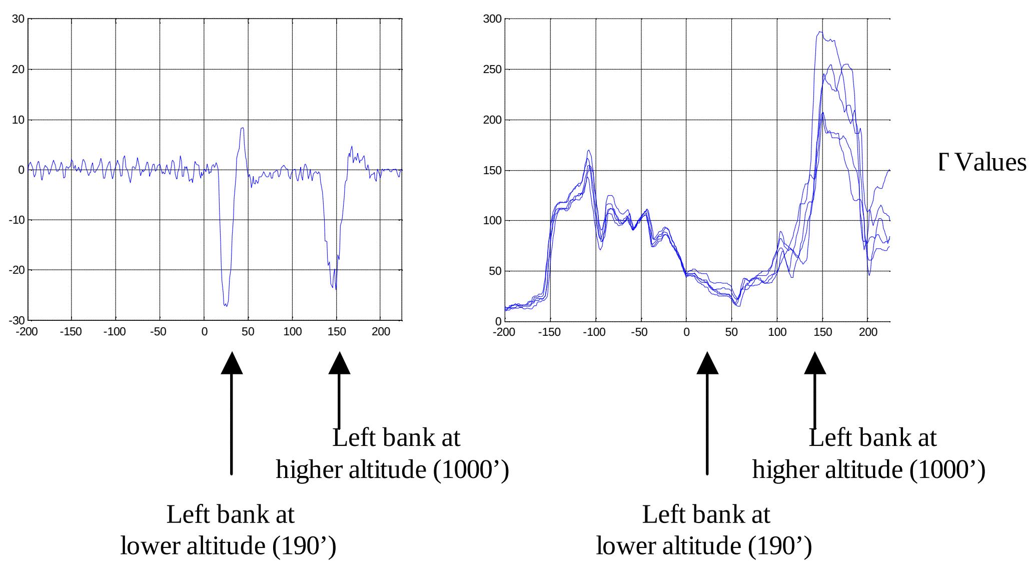


Figure 11. Correlation between roll maneuvers and increase in *T*-values.

5.2 Comparison of USGS versus JEPP

The integrity monitor's performance was tested using both the USGS and JEPP terrain databases. Figure 12 shows an excerpt of the flight test results for approaches to runway 25 on September 1st 2001. The USGS *T*-values are overall higher than the JEPP *T*-values. The reason for this discrepancy can be observed in Figure 14 where, for both terrain databases, the synthesized and database terrain profiles are plotted.

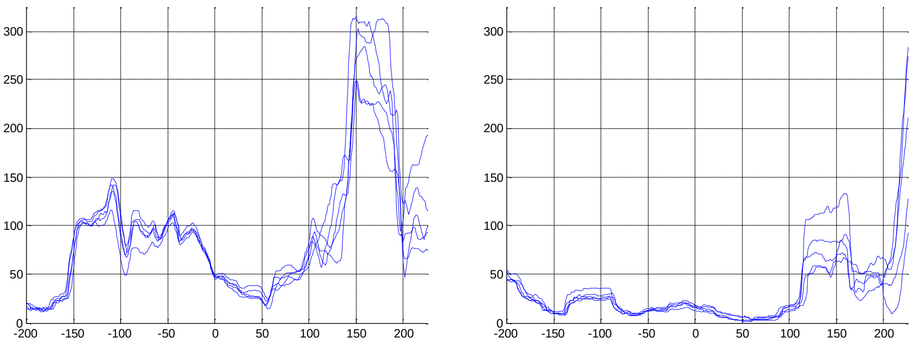


Figure 12. Terrain database comparison for all approaches to runway 25 - (a) Left: USGS, (b) Right: JEPP.

Large quantization errors, indicated by the circles, cause an inconsistency between the synthesized and database terrain profiles. Because the *T*-values are directly related to the difference between the synthesized and database terrain elevations, the magnitude of the *T*-value will be more significant when using the USGS data. For given example, the quantization error causes the test statistic to exceed the threshold, and in an operational environment an aural or visual alert would be generated; in other words, the integrity monitor successfully detected a terrain database deficiency. One possible explanation for the presence of the large quantization errors is that this USGS 1-degree product is a digital representation of a cartographic map. This illustrates one way that source data creation method may affect operational performance.

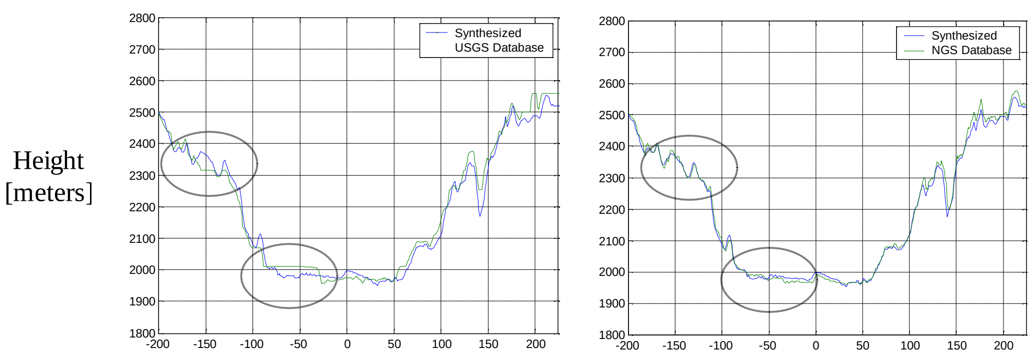


Figure 13. Synthesized versus database terrain profiles - (a) Left: USGS, (b) Right: JEPP.

5.3 Comparison of WAAS versus KGPS

The DGPS elevation measurement, h_{DGPS}, can be obtained post-flight from the truth reference, KGPS, or real -time in-flight from the WAAS receiver. Figure 14 shows a comparison of the KGPS and WAAS *T*-value results for the approaches to runway 07 on September 1st 2001. The terrain database elevations were retrieved from the JEPP terrain database. The results show a deteriorated integrity monitor performance when using KGPS even though KGPS is specified to have better accuracy.

(a) **(b)**

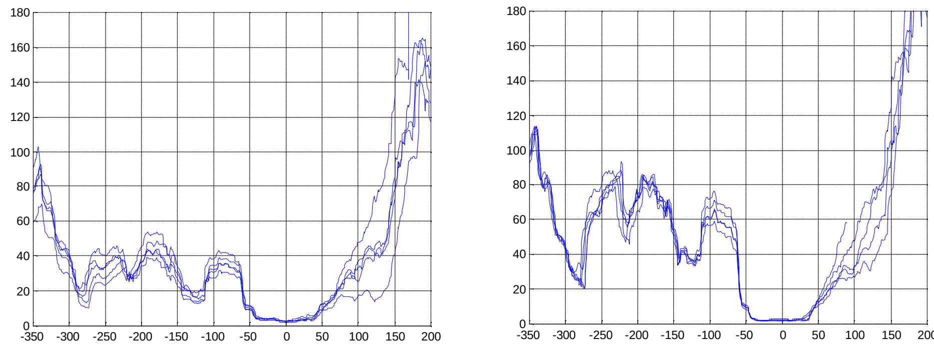


Figure 14. T -values for approach to runway 07 (09/01/01) using
(a) WAAS elevation measurements, (b) KGPS elevation measurements.

The reason for this can be twofold: (1) a terrain database error is present and WAAS provides an elevation measurement with an error of similar magnitude and opposite sign, or (2) the KGPS elevation measurements are erroneous or referenced to the wrong vertical datum. To further investigat e this phenomenon, all elevations, measured and retrieved, were subtracted and the mean and standard deviation of the residual error were calculated for all approaches to runway 07 on September 1 st 2001. Table 3 shows the results of this comparison. Note that table 3 also includes a comparison between the two databases, USGS and JEPP, and the highly accurate National Geodetic Survey terrain data.

Table 3. Mean and standard deviation of the residual errors.

Terrain Pair	Mean (m)	Stdev (m)
UEPP -kGPS	10.3	13.2
UEPP -WAAS	-1.4	13.0
NGS-kGPS	11.8	12.2
JEPP -NGS	-1.5	11.7
NGS-WAAS	-0.1	12.1
WAAS-kGPS	11.7	1.2

Table 3 indicates t hat the standard deviation is well within specification, however, the mean is off nominal and approximately equal in magnitude for all comparisons with KGPS. Note that the vertical datum for both the JEPP and NGS data is the North American Vertical Datum (NAVD) 88. Although the true cause has not yet been identified, the most likely cause of the inconsistency is a mismatch of vertical datums.

6. SUMMARY AND CONCLUSIONS

The three DIME flight test objectives stated in Section 1.4 have been met: (1) The opera tional behavior of the integrity monitor has been characterized using the COTS B-757 triple-redundant radar altimeter set. The B -757 FM-CW radar altimeters show a consistent behavior for all approaches, and no "spot" algorithm is required for operation at lower attitude. At higher altitudes the effects of the terrain undulations on the radar altimeter measurement performance becomes more obvious and will require appropriate modeling to prevent a false alarm rate that exceeds the specification significantly. Appropriate modeling or application of algorithms such as the "spot" algorithm may be necessary to guarantee an integrity capability at higher altitudes. (2) The quality of the USGS and JEPP databases has been assessed. The 1-degree USGS product was shown to contain large quantization errors that cause the terrain database to perform off-nominal, and integrity alarms were generated. Using cartographic maps as source is believed to be the reason for these quantization effects. The Jeppesen terrain database, derived from a USGS 7.5-minute product, seems to perform nominally. And (3) the performance of the monitor in a region characterized by severe terrain undulations was observed. Inconsistent integrity monitor performance between the use of KGPS data and WAAS receiver data can more than likely be attributed to a mismatch of the vertical datums. This illustrates the importance of a vertical and horizontal datum requirement in the system requirements.

The performance of the proposed real-time terrain database integrity monitor looks promising, however SVS operational requirements must be specified in order to determine whether the altitude limits imposed by the COTS RAs is sufficient and whether the specified minimum detectable biases used at EGE are acceptable. Depending on these requirements, higher accuracy databases, such as those obtained from the Shuttle Radar Topography Mission (SRTM), longer integration times, or augmentation with forward-looking based sensor integrity schemes may be necessary to guarantee terrain database integrity during all SVS operational scenarios.

ACKNOWLEDGEMENTS

The authors would like to thank NASA's B-757 ARIES flight crew for their support and expertise during the flight-testing at EGE. In particular, Stella Harrison, Kevin Shelton, and Charles Howell were key contributors to the successful implementation of the DEM integrity monitor function on the B-757. The work presented in this paper was supported and funded through NASA under Cooperative Agreement NCC-1-351.

REFERENCES

1. Williams, D., et al., "Concept of Operations for Commercial and Business Aircraft Synthetic Vision Systems – Version 1.0," NASA Langley Research Center, January 2001.
2. "Terrain Awareness and Warning Systems", Federal Register - Rules and Regulations, FR Doc 00-7595, Vol. 65, No. 61, pp. 16735-16756, March 27, 2000.
3. "International Standards and Recommended Practices – Aeronautical Information Services", ICAO Annex 15, International Civil Aviation Organization, July 1997.
4. "Software Considerations in Airborne Systems and Equipment Certification", DO-178B, RTCA, December 1992.
5. "International Standards and Recommended Practices – Aerodromes", ICAO Annex 14, International Civil Aviation Organization, July 1999.
6. "World Geodetic System – 1984 (WGS-84) Manual", Doc 9674-AN/946, International Civil Aviation Organization, 1997.
7. "Standards for Processing Aeronautical Data", DO-200A, RTCA, September 1998.
8. "User Requirements for Terrain and Obstacle Data", ED-98, EUROCAE, February 2002.
9. "User Requirements for Aerodrome Mapping Information", DO-272, RTCA, October 12, 2001.
10. Gray, R. A., "In-flight Detection of Errors for Enhanced Aircraft Flight Safety and Vertical Accuracy Improvement Using Digital Terrain Elevation Data with an Inertial Navigation System, Global Positioning System and Radar Altimeter," Ph.D. Dissertation, Ohio University, Athens, Ohio, June 1999.
11. Uijt De Haag, M., Young, S., And Gray, R., "A Performance Evaluation of Elevation Database Integrity Monitors for Synthetic Vision Systems", 8th International Conference on Integrated Navigation Systems, Saint Petersburg, Russia, May 28-30, 2001.
12. Uijt De Haag, M., Sayre, J., Campbell, J., Young, S., And Gray, R., "Flight Test Results of a Synthetic Vision Elevation Database Integrity Monitor", International Society for Optical Engineering (SPIE) Aerosense Conference, Orlando, Florida, April 16-20, 2001.
13. "Physical geodesy – WGS84 Earth Gravity Model," http://www.nima.mil/GandG/wgs-84, March 1, 2002.
14. Uijt de Haag, M., Campbell, J., And Gray, R. A., "A Terrain Database Integrity Monitor for Synthetic Vision Systems," Proceedings of the 19th Digital Avionics Systems Conference, Philadelphia, 7-13 October 2000.